Network Synchronization among Femtocells

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***Abstract*—To successfully deploy femtocells overlaying the Macrocell as a two-tier that had been shown greatly benefiting communications quality in various manners, it requires to mitigate cross-tier interference between the Macrocell and femtocells, as well as intra-tier interference among femtocells. For this purpose, solutions for interference mitigation have been proposed for femtocells in literatures. However, an essential assumption of these solutions is that all femtocells and the Macrocell shall be synchronized. Such a (network) synchronization of the Macrocells and user deployed femtocells create diverse challenges from conventional synchronization among Macrocells. Existing solutions therefore leverage the global positioning system (GPS) or the wired backhaul (IEEE 1588) to synchronize the Macrocell and all femtocells, however, they are infeasible for LTE-Advanced femtocells suffering a severe penetration loss of GPS signals and a severe jitter on the backhaul with heterogeneous protocols. As a consequence, each femtocell achieving a timing consensus by leveraging synchronization signals broadcasted by the Macrocell or by the neighboring femtocells turns out to be the possible solution. In this paper, we propose a network synchronization algorithm for femtocells. By only utilizing existing synchronization signals, the proposed network synchronization algorithm achieves the timing consensus among femtocells with and without the present of the Macrocell. Yielding an extremely low computational complexity, the proposed algorithm achieves the essential assumption of interference mitigation solutions in literatures and thus enabling the femtocell technology.**

***Index Terms*—Femtocells, LTE-Advanced, network synchronization.**

I. Introduction

FEMTOCELLS had been recognized as an essential technology to achieve high data rate requirements toward the forth generation (4G) wireless system defined by IMT-Advanced [1], [2]. Femtocells, formed by home base stations (abbreviated as HeNBs in 3GPP), are haphazardly deployed by users to the indoor environment overlaying existing Macrocells. However, it is also such high data rate requirements that result in the infeasibility of frequency partitions among all femtocells and the Macrocell. The Macrocell and all femtocells thus shall fully reuse all available common spectrum. Such universal frequency reuse consequently induces severe interference between the Macrocell and the femtocell, and among femtocells under a dense deployment. Such an interference problem has been considered as the most critical issue for a successful realization of the femtocell technology in LTE-Advanced [3], [4] and an effective autonomous interference mitigation scheme thus is urgently required. Recently, this challenge attracts a number of effective solutions for interference mitigation between the Macrocell and femtocells [5]–[8], and among femtocells [9]. However, one critical assumption in these solutions is a well timing synchronization between the Macrocell and all femtocells overlaying the Macrocell.

To achieve such critical network synchronization between the Macrocell and all femtocells overlaying the Macrocell, IEEE 1588 [10] is proposed in WiMAX to deliver timing information from a synchronization server to all femtocells through the wired backhaul, by which each HeNB can measure the timing difference between the HeNB itself and the centralized synchronization server [11], [12]. Each HeNB thus can correct its clock by estimated timing offset. However, in LTE-Advanced femtocells, each femtocell connects to the network by users' own IP connectivity such as Ethernet or fiber optics lines. There can be a number of intermediate nodes between the femtocell and the synchronization server. Thus, measuring the delay and jitter of packets carrying timing stamps transmitted over heterogeneous intermediate nodes (with diverse protocols) is a very challenging task. As a result, IEEE 1588 may not be feasible for LTE-Advanced femtocells. A solution for the network synchronization via the *air interface* thus is urgently required by LTE-Advanced.

In LTE-Advanced, base stations of Macrocells (abbreviated as eNBs) are commonly equipped with the global positioning system (GPS). By the GPS, all Macrocells are well synchronized. However, since femtocells are typically deployed in the indoor environment and suffer severe signal attenuation, especially the signal coming from GPS satellites. The GPS is consequently not adopted by femtocells. Therefore, synchronization between the Mcrocell and all femtocells overlaying the Macrocell can not be achieved by the GPS. To achieve the timing consensus among the Macrocell and all femtocells, one possible solution is that each HeNB synchronizes to Macrocells by leveraging synchronization signals broadcasted by eNBs. These synchronization signals are broadcasted for user equipments (UEs) such that UEs can synchronize to the eNB. Therefore, synchronization between the Macrocell and the femtocell can be achieved. If all femtocells can synchronize to the Macrocell, synchronization among femtocells can also be achieved. However, such an ideal situation may not generally hold, since synchronization signals from Macrocell may not certainly be received by all femtocells, especially for some femtocells suffering severe signal attenuation.

For femtocells that can not successfully synchronize to the Macrocell, one possible solution to achieve the network synchronization turns out to be that these femtcoells synchronize to neighboring femtocells by leveraging synchronization signals from neighbor HeNBs. However, in LTE-Advanced, there is no common interface among femtocells. Communications among femtocells thus are unavailable. As a result, a HeNB synchronized to Macrocell can not notify other HeNBs of its successful synchronization to the Macrocell. Consequently, a HeNB that can not synchronize to the Macrocell faces a

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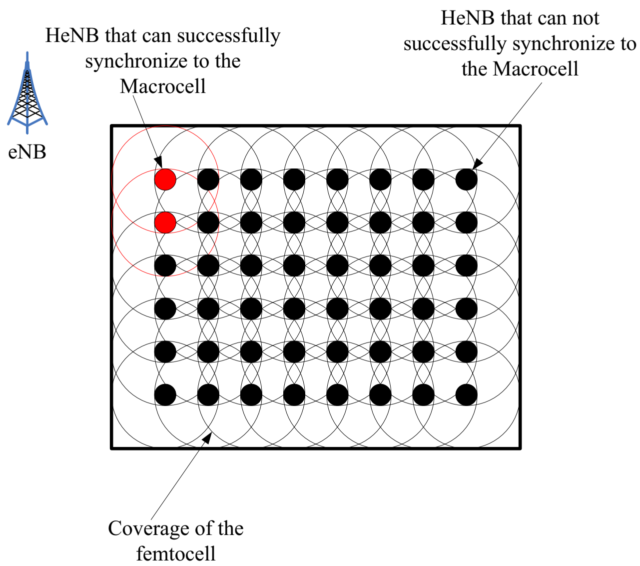

Fig. 1. Femtocells are deployed to fully cover whole area of the building (i.e., the qusi-complete graph deployment) where certain femtocells can successfully synchronize to the Macrocell, while other femtocells can not.

challenge, it does not know which of its neighboring HeNBs achieves a successful synchronization to the Macrocell. If a HeNB keeps synchronizing to another HeNB without the synchronization to the Macrocell, the issue of the timing oscillation among femtocells occurs. That is, timings of HeNBs never converge to a common value.

To combat such timing oscillation issue due to the unavailability of information (whether a neighboring HeNB achieves a successful synchronization to the Macrocell) exchanges among femtocells, we develop a network synchronization algorithm for each HeNB. The proposed network synchronization algorithm achieves a successful synchronization among all femtocells overlaying the Macrocell under following critical constraints in the LTE-Advanced femtcoells architecture: (i) Each HeNB only utilizes existing synchronization signals broadcasted by the eNB of the Macrocell or neighboring HeNB. Therefore, there is no impact on the existing femtcoells architecture in LTE-Advanced. (ii) For a HeNB that can not synchronize to the Macrocell, the knowledge of which its neighboring HeNB can synchronize to the Macrocell is not required. (iii) Even though none of femtocells can successfully synchronize to the Macrocell, the synchronization among all femtocells can also be achieved. (iv) The proposed algorithm yields an extreme low computational complexity. We mathematically prove the convergency of the proposed network synchronization algoith, and thus resolve the challenge of the fundamental assumption to enable existing autonomously interference mitigation solutions.

II. System Model

In this paper, we consider a typical dense femtocells deployment. That is, the enterprise scenario of femtocells. In this scenario, M femtocells are deployed in a building to fully cover whole area of the building, as shown in Fig. 1. To specifically describe such a scenario, following definitions are made.

Definition 1. *We say that there is a link between two HeNBs if these two HeNBs can receive synchronization signals from each other.*

Please note that the existence of a link between two HeNBs does not suggest that these two HeNBs can exchange data/information with each other. According the femtocell architecture defined by LTE-Advanced, there is no interface among femtocells for communications with each other [3].

Definition 2. *The deployment of femtocells is a qusi-complete graph if there exists a path (composed of multiple successive links) between any two HeNBs of the deployment.*

By Definition 2, the considered enterprise scenario of femtocells is deployed as a qusi-complete graph. In such a qusi-complete graph, only some HeNBs can successfully receive synchronization signals from the Macrocell to synchronize to the Macrocell, while other femtocells deployed deeply inside the building may not receive synchronization signals from the Macrocell. A femtocell that can synchronize to the Macrocell is unable to notify other femtocells of this information. Therefore, femtocells unable to synchronize to the Macrocell can only leverage synchronization signals broadcasted by its neighboring HeNBs to achieve the network synchronization, without knowing which of its neighboring HeNBs can synchronize to the Macrocell.

III. Femtocell Network Synchronization Algorithm

For HeNBs able to synchronize to the Macrocell, HeNBs only need to synchronize to the Macrocell according to the conventional synchronization procedure adopted by UEs. On the other hand, for femtocells unable to synchronize to the Macrocell, HeNBs shall synchronize to its neighboring HeNBs. Such a network synchronization algorithm is proposed as follows.

Network Synchronization Algorithm:

Step 1) Each HeNB runs a Poisson clock which is independent to other HeNBs'. That is, at each subframe, the HeNB decides to proceed synchronization or not according to the Poisson process.

Step 2) Upon the expiration of the Poisson clock, a HeNB that can successfully receive synchronization signals broadcasted by the eNB (of the Macrocell) synchronizes to the Macrocell by the conventional synchronization method adopted by UEs.

Step 3) Upon the expiration of the Poisson clock, if the HeNB can not successfully receive synchronization signals broadcasted by the eNB, then the HeNB randomly selects n neighboring HeNBs and receive synchronization signals broadcasted by the selected HeNBs, $n \leq N$, where N is the total number of neighboring HeNBs of the considered HeNB. This process is conducted according to a Poisson clock [13].

Step 3a) Denote the current timing of the considered HeNB as x_0 and denote current timings of selected

n neighboring HeNBs as $x_1, \ldots, x_n$. x_0 is updated by

$$x_0 = \sum_{i=0}^{n} \lambda_i x_i, \tag{1}$$

where $\sum_{i=0}^{n} \lambda_i = 1$ and $\lambda_i \geq 0$ for all i.

Step 4) Repeat Step 1 to Step 3.

In Step 3a, the timing of the HeNB is updated according to the "convex combination" of the current timing of the HeNB and timings of selected HeNBs. Such a convex combination timing update results in an extremely low computational complexity, this it is very suitable for the HeNB with limited computational capability. In addition, this convex combination timing update also facilitates the convergence of timings of all femtocells. In the following section, we devote to provide the mathematical foundation on the convergence (network synchronization) of the proposed algorithm.

IV. Convergence of the Proposed Network Synchronization Algorithm

For a HeNB that can not receive synchronization signals from the Macrocell, the timing update can be described by the equation of the form

$$x_0^{t+1} = W(t)\mathbf{x}^t, \tag{2}$$

where x_0^{t+1} is the timing of the considered HeNB after $t+1$ iterations, $\mathbf{x}^t = [x_0^t, x_1^t, \ldots, x_n^t]^{\mathrm{T}}$ and $W(t)$ is an $n+1 \times n+1$ matrix. Please note that, since $\lambda_0, \lambda_1, \ldots, \lambda_n$ are randomly and independently selected across the time, $W(t)$ is independent across the time.

The following theorem and the corresponding proof suggest the convergence of the proposed network synchronization algorithm.

Theorem 1. *If all femtocells overlaying the Macrocell adopt the proposed network synchronization algorithm, all timings of femtocells converge in expectation to a common value.*

Proof: To prove the convergence, we firstly need to show that $W(t)$ is a projection matrix. That is, $W^2(t) = W(t)$. If $W(t)$ is a projection matrix, $W(t)$ shall stratify following properties

$$\mathbf{1}^T W(t) = \mathbf{1}^T \text{ and } W(t)\mathbf{1} = \mathbf{1}. \tag{3}$$

That is, $W(t)$ shall be *doubly stochastic*. Since the well known Birkhoff-von Neumann theorem suggests that a matrix is *doubly stochastic* if and only if the matrix is a convex combination of permutation matrices. Since x_0^t is updated by the convex combination of $x_0^t, x_1^t, \ldots, x_n^t$, (1) suggests that $W(t)$ is *doubly stochastic*. Therefore, the evolution of x_0^{t+1} can be expressed by

$$x_0^{t+1} = W(t)\mathbf{x}^t = \prod_{k=0}^{t} W(k)\mathbf{x}^0. \tag{4}$$

Since $W(t)$ is selected independent across the time, the expectation of (4) can be written by

$$\mathbb{E}x_0^{t+1} = \mathbb{E}(\prod_{k=0}^{t} W(k))\mathbf{x}^0 = (\mathbb{E}W)^{t+1}\mathbf{x}^0. \tag{5}$$

TABLE I
Simulation parameters and assumptions for performance evaluations

Parameters	Values/assumptions
Carrier frequency	2 GHz
Frame length	1 ms
Small scale and shadow fading	According to [15]
eNB TX power	46 dBm
HeNB TX power	20 dBm
Synchronization Signal broadcast period	5ms
Modulation	QPSK
Number of femtocells	9 and 25

Since $\mathbb{E}W$ is a convex combination of $W(t)$, $\mathbb{E}W$ is also *doubly stochastic*. In addition, since femtocells are deployed as a qusi-complete graph, the expected evolution of x_0^{t+1} follows an irreducible and aperiodic Markov chain that has $\sum_{i=0}^{n} \lambda_i x_i^t$ as the stationary distribution. Thus, we complete the proof that all timings of femtocells converge in expectation to $\sum_{i=0}^{n} \lambda_i x_i^t$ ■

In additional to ensure the convergence, the convergence rate is also an important performance matric, since a too long convergence time may not be acceptable in practice. In this paper, we adopt following measurement of the convergence time. This measurement is widely adopted in literatures on measuring the convergence rate.

Definition 3. *The ϵ-convergence time is the earliest iteration in which $\boldsymbol{x}^t$ is ϵ close to the normalized consensus with probability larger than $1-\epsilon$,*

$$T_{con}(\epsilon) = \sup_{\boldsymbol{x}^0} \arg \inf_{t=0,1,\ldots} \{\mathbb{P}(\frac{\|\boldsymbol{x}^t - \sum_{i=0}^{n} \lambda_i x_i^t\|}{\|\boldsymbol{x}^0\|} \geq \epsilon) \leq \epsilon\}. \tag{6}$$

Under such a convergence rate measurement, we then provide the convergence rate of the proposed network synchronization algorithm in the following theorem.

Theorem 2. *The convergence rate of the proposed network synchronization rate is $T_{con}(\epsilon) = \Theta(M^2 \log \epsilon^{-1})$.*

Proof: From [14], it is known that

$$T_{con}(\epsilon) = \Theta(\frac{\log \epsilon^{-1}}{1 - \lambda_2(\mathbb{E}W)}), \tag{7}$$

where $\lambda_2(\mathbb{E}W)$ is the second largest eigenvalue of the matrix $\mathbb{E}W$. For the considered qusi-complete graph deployment, it has been shown that $\lambda_2(\mathbb{E}W) = 1 - \frac{1}{\lambda^2}$ [14]. Therefore, $T_{con}(\epsilon) = \Theta(M^2 \log \epsilon^{-1})$ for the proposed network synchronization algorithm. ■

V. Performance Evaluations

To evaluate the performance of the proposed network synchronization algorithm, we adopt the system parameters of LTE-Advanced in our simulation [15]. In this simulation, femtocells are deployed in a grid topology (as shown in Fig. 1). The distance between any two HeNBs is 15m. System parameters and assumptions are provided in detail in Table I.

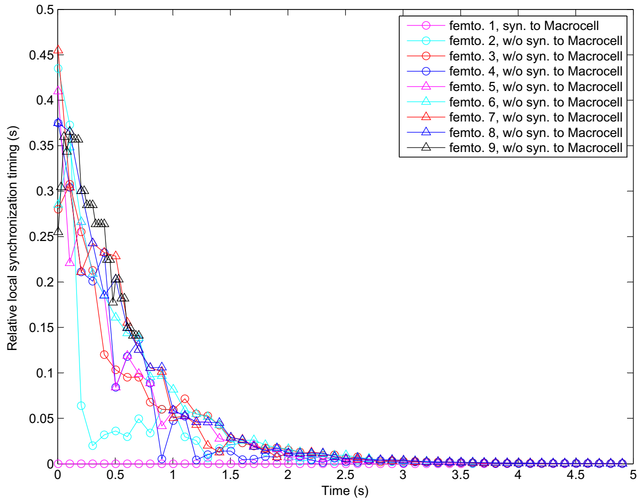

Fig. 2. Timing dynamics of 9 femtocells in which 1 femtocell can successfully synchronize to the Macrocell.

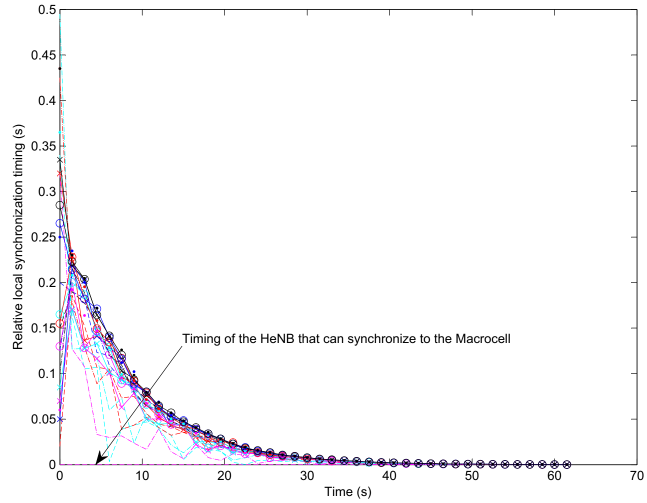

Fig. 4. Timing dynamics of 25 femtocells in which 1 femtocell can successfully synchronize to the Macrocell.

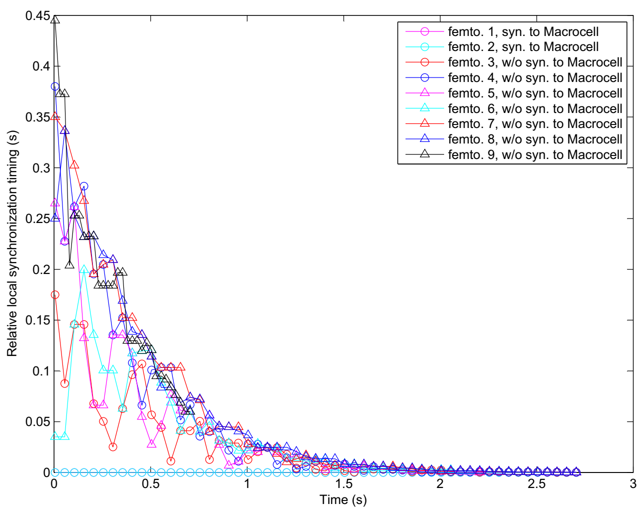

Fig. 3. Timing dynamics of 9 femtocells in which 2 femtocells can successfully synchronize to the Macrocell.

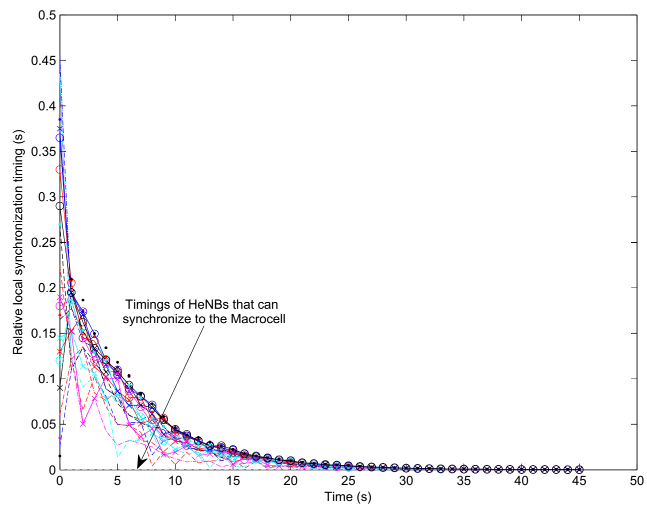

Fig. 5. Timing dynamics of 25 femtocells in which 2 femtocells can successfully synchronize to the Macrocell.

A. Some HeNBs with a Successful Synchronization to the Macrocell

We first evaluate the performance of the network synchronization with a certain number of femtocells among total M femtocells that are able to successfully synchronize to the Macrocell. All these femtocells that can successfully synchronize to the Macrocell locate on the boundary of the building.

Fig. 2 shows timing dynamics of $M = 9$ femtocells among which one femtocell can successfully synchronize to the Macrocell (denoted by the first femtocell). We can observe from Fig. 2 that all timings of 8 femtocells that can not successfully synchronize to the Macrocell align to the timing of the femtocell with the successful synchronization to the Macrocell in 3s. This result suggests the effectiveness of the proposed network synchronization algorithm. In Fig. 3, we investigate timing dynamics of $M = 9$ femtocells among which two femtocells can successfully synchronize to the Macrocell. We can observe from Fig. 3 that the more the femtocells can successfully synchronize to the Macrocell, the faster timings of other femtocells converge to the timing of the Macrocell.

In Fig. 4 and Fig. 5, we evaluate the performance of timing dynamics of $M = 25$ femtocells, among which, there are one and two femtocells with a successful synchronization to the Macrocell, respectively. We can observe from Fig. 4 and Fig. 5 that, as M increases, the time for the converge increases increases with the order of M^2. These results follow our analysis of the convergence rate in Theorem 2.

B. None of HeNBs with Successful Synchronization with the Macrocell

In this subsection, we evaluate another merit of the proposed network synchronization algorithm under the condition that none of femtocells can successfully synchronize to the Macrocell. Fig. 6 shows timing dynamics of 9 femtocells and none of these 9 femtocells can successfully synchronize to the Macrocell. We can observe from Fig. 6 that all these 9

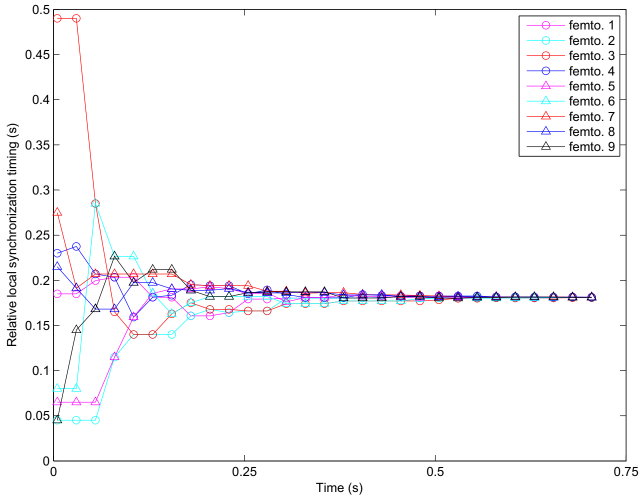

Fig. 6. Timing dynamics of 9 femtocells in which none of femtocells can successfully synchronize to the Macrocell.

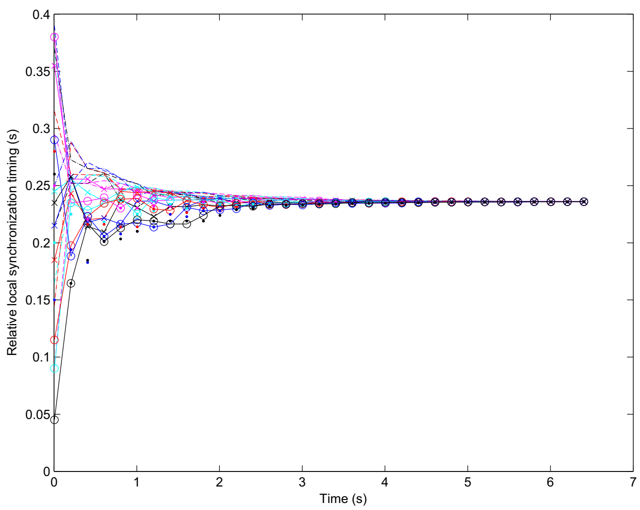

Fig. 7. Timing dynamics of 25 femtocells in which none of femtocells can successfully synchronize to the Macrocell.

femtocells achieve a timing consensus in 0.5s. This synchronization time is shorter than that of the condition that there are certain femtocells with a successful synchronization with the Macrocell. This result is not surprising. If there are certain femtocells with a successful synchronization to the Macrocell, all femtocells shall have the consensus with these femtocells with a successful synchronization. It requires a large number of iterations.

Fig. 7 shows timing dynamics of 25 femtocells and none of these 9 femtocells can successfully synchronize to the Macrocell. This result also suggests the convergence according to the rate $T_{con}(\epsilon) = \Theta(M^2 \log \epsilon^{-1})$.

VI. Conclusion

In this paper, we resolve the most critical issue on the network synchronization of femtocells to achieve the critical assumption of autonomous interference mitigation solution in literatures. Yielding a very limited computational complexity and imposes no impacts on the system architecture of the existing femtocell architecture in 3GPP, the proposed network synchronization algorithm enables each femtocells to achieve a successful synchronization among all femtocells with and without the present of the Macrocell. Thus, it can be smoothly applied to LTE-Advanced femtocell to serve urgent needs of the standardization progress in 3GPP.

References

[1] D. N. Knisely, T. Toshizawa, and F. Favichia, "Standardization of femtocells in 3GPP," *IEEE Commun. Mag.*, vol. 47, no. 9, pp. 68–75, Sep. 2009.

[2] V. Chandrasekhar and J. G. Andrews, "Femtocell networks: A survey," *IEEE Commun. Mag.*, vol. 46, no. 9, pp. 59–67, Sep. 2008.

[3] 3GPP TS 36.300 V10.2.0, "Evolved universal terrestrial radio access (E-UTRA) and evolved universal terrestrial radio access network (E-UTRAN)," Dec. 2010.

[4] 3GPP TR25.967 V9.0.0, "Home node B radio frequency (RF) requirements (FDD)," 2009.

[5] S.-Y. Lien, C.-C. Tseng, K.-C. Chen, and C.-W. Su, "Cognitive radio resource management for QoS guarantees in autonomous femtocell networks," in *Proc. IEEE ICC*, 2010.

[6] Institute for Information Industry and Coiler Corporation, "R4-093196: Interference mitigation for HeNB by channel measurements," in *3GPP TSG RAN WG4 Meeting 52*, 2009.

[7] ——, "R4-094002: Channel measurement based interference mitigation schemes for HeNBs," in *3GPP TSG RAN WG4 Meeting 52bis*, Oct. 2009.

[8] ——, "R1-105299: Considerations on grouping based interference mitigation among co-located femtocells," in *3GPP TSG RAN WG1 Meeting 62bis*, Oct. 2010.

[9] S.-Y. Lien, Y.-Y. Lin, and K.-C. Chen, "Cognitive and game-theoretical radio resource management for autonomous femtocells with QoS guarantees," to appear in *IEEE Trans. Wireless Commun.*, 2011.

[10] IEEE Instrumentation and Measurement Society, "IEEE 1588 standard for a precision clock synchronization protocol for networked measurement and control systems," in *IEEE Std 1588*, 2008.

[11] J. Yoon, J. Lee, and H. S. Lee, "Multi-hop based network synchronization scheme for femtocell systems," in *Proc. IEEE PIMRC*, 2009.

[12] I. Hwang, Y. Kang, H. Kim, and S. Kim, "Synchronization issue for mobile WiMAX femtocell," in *Proc. ICTC*, 2010.

[13] A. G. Dimakis, S. Kar, J. M. F. Moura, M. G. Rabbat, and A. Scaglione, "Gossip algorithms for distributed signal processing," *Proc. IEEE*, vol. 98, no. 11, pp. 1847–1864, Jun. 2010.

[14] S. Boyd, A. Ghosh, B. Prabhakar, and D. Shah, "Ransomized gossip algorithms," *IEEE Trans. Inf. Theory*, vol. 52, no. 6, pp. 2508–2530, Jun. 2006.

[15] 3GPP TR 36.814 V9.0.0, "Further advancements for E-UTRA physical layer aspects," Mar. 2010.